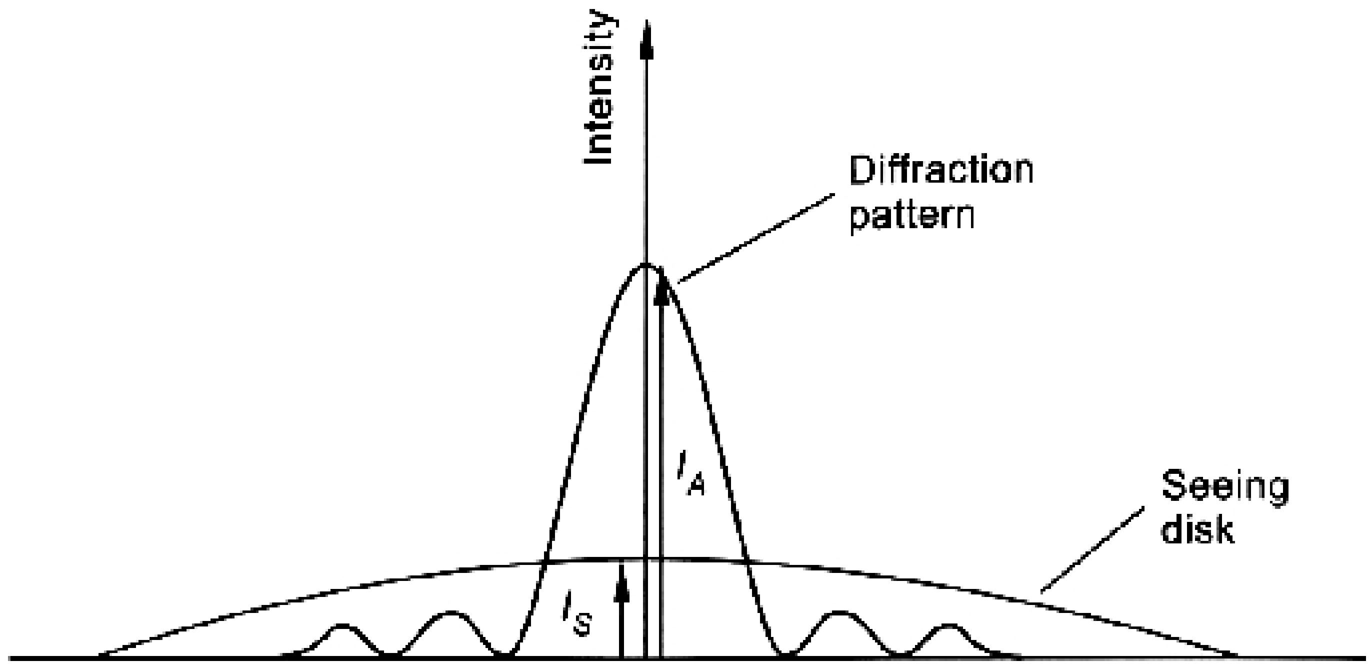
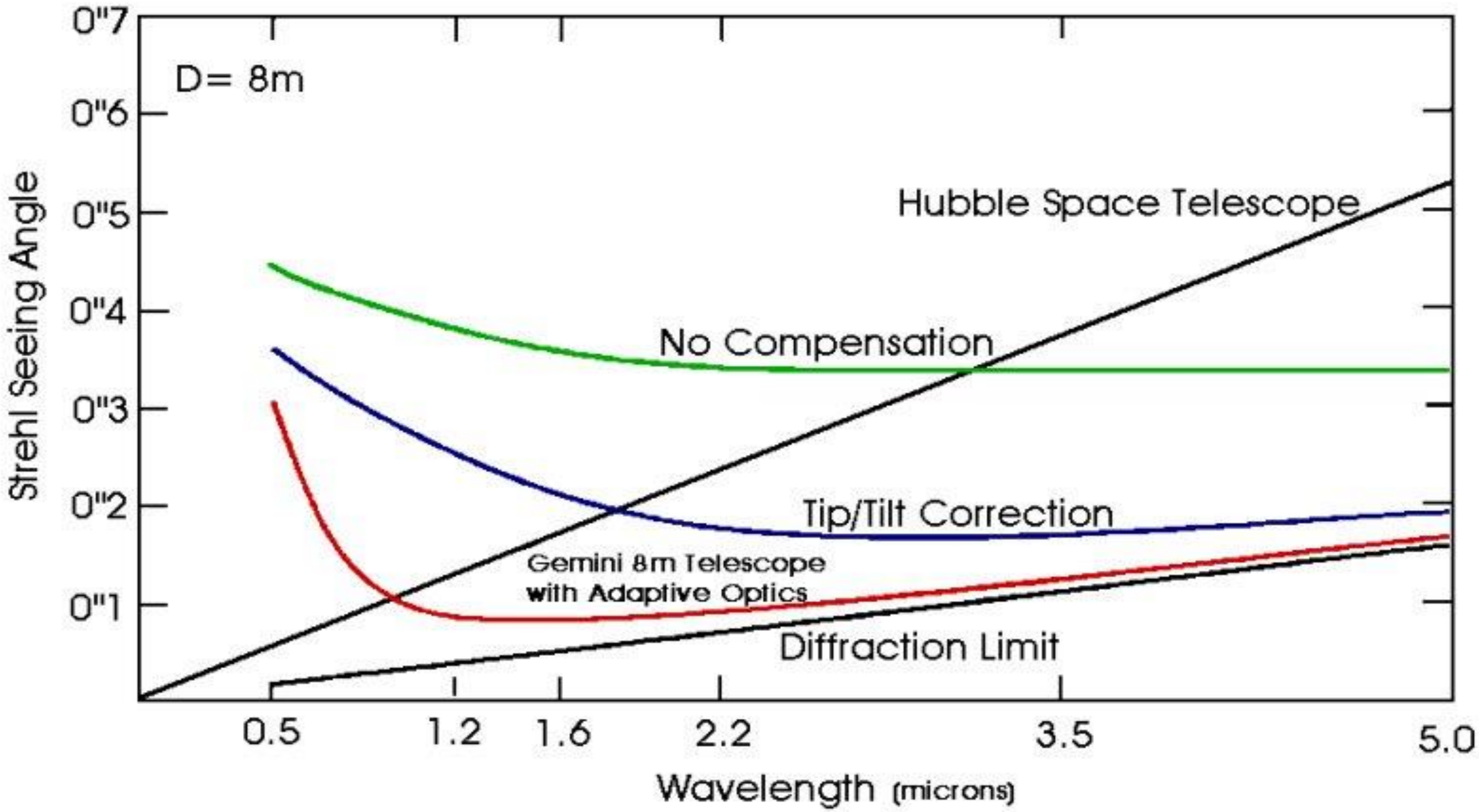
Strehl Ratio



The ratio of the peak intensity of the measured image to that calculated from the diffraction pattern of the telescope optics is the Strehl Ratio

Wavelength dependence

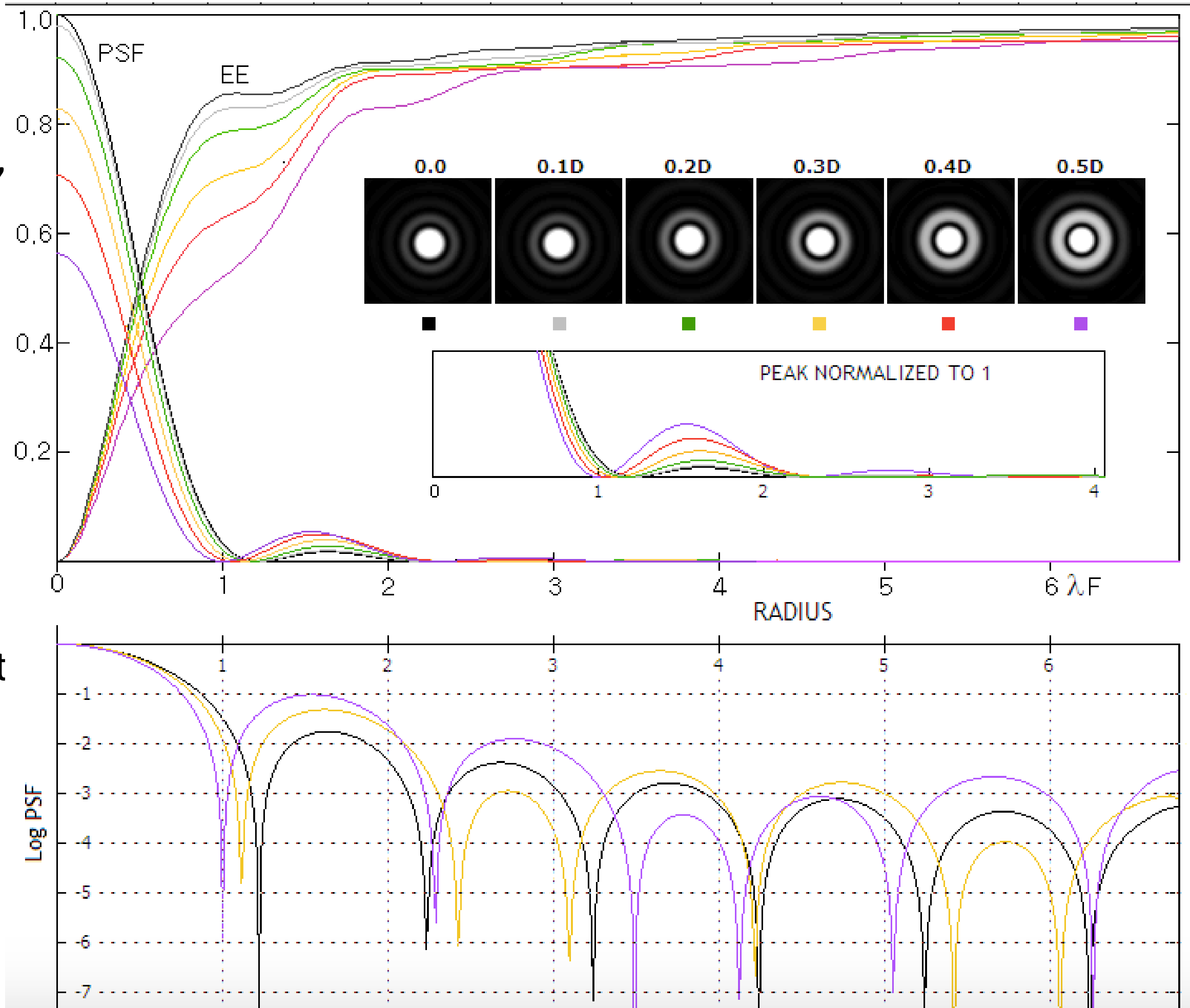


- To a good approximation, atmospheric turbulence follows a Kolmogorov spectrum, with the coherence scale
  $r_0(\lambda) \sim r_0(\lambda_0)\,(\lambda/\lambda_0)^{1.2}(\cos(z))^{0.6}$.
- so that the seeing disk in the IR is smaller than in the visible : FWHM $\alpha\ \lambda^{-0.2}$
- At 2µm it is 0.75 times that at 0.5µm, and at 10µm it is 0.55.

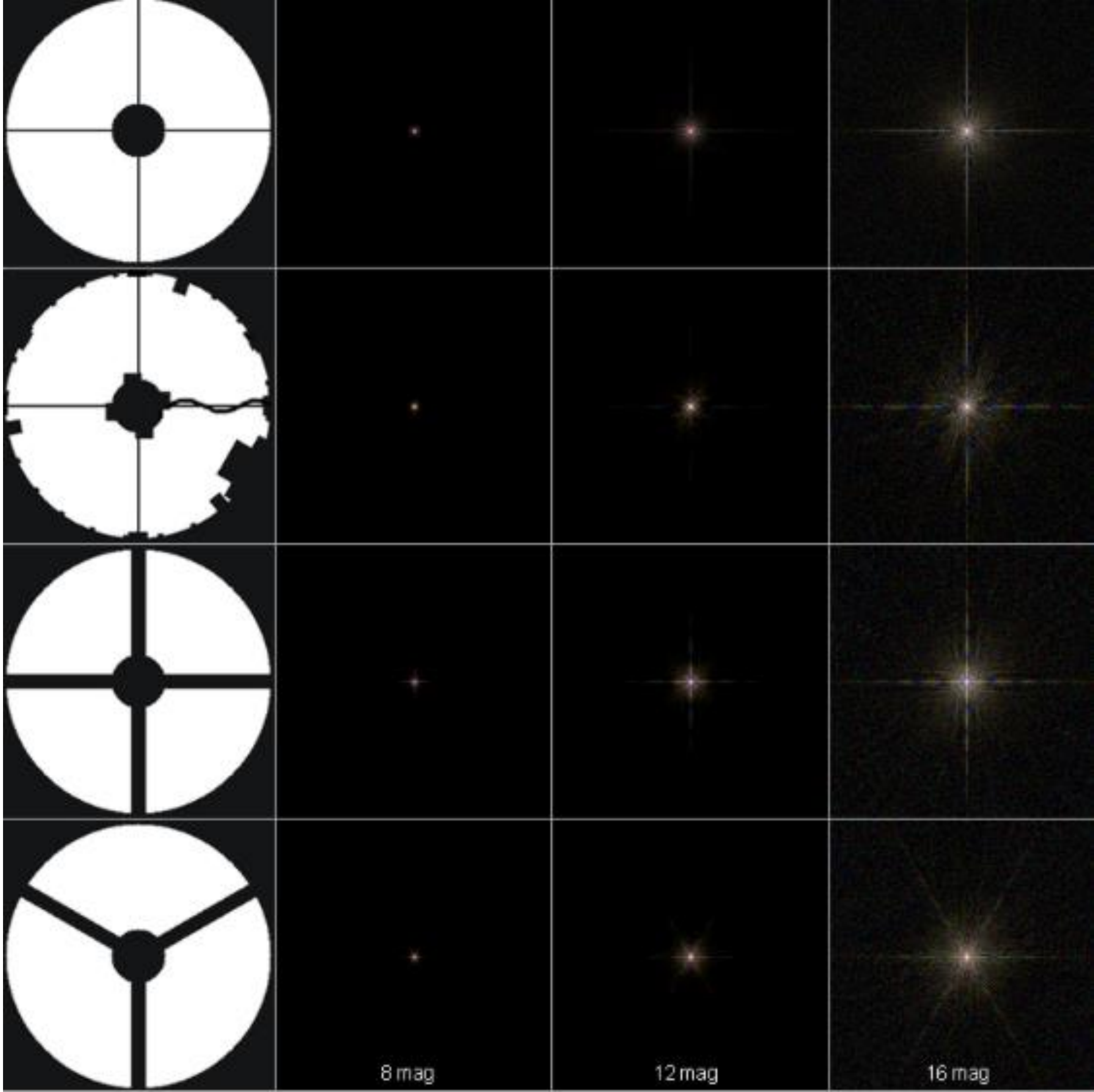
Effect of the Telescope Central Obstruction

pushes more power into the diffraction rings, but also narrows the central maximum

It also reduces the flux collected and produces greater discontinuities in the wavefront in the telescope pupil



- The point spread function delivered by the telescope depends on the mirror surfaces and alignment, the atmosphere and the effects of the central obstruction and secondary mirror vanes on the telescope pupil.



R Pascal

Coherence time

- The simplest model assumes that the turbulent atmosphere is blown across the telescope aperture by the wind.
- In this case, the characteristic (Greenwood) frequency of the atmosphere can be approximated by:
- $f_G = 0.43\, V_{wind}/r_0$ which, with $r_0 \sim\lambda^{1.2}$, means that the coherence time, $t_0 \sim\lambda^{1.2}$ and is in the range ~2 to 20msec from the visible to the IR.
- The frame time to freeze the atmosphere is longer at IR wavelengths while the number of r_0 subapertures in the telescope pupil is smaller
- At long wavelengths, r_0 can approach the size of the telescope aperture and low order correction will be effective. At shorter wavelengths, higher order correction – Adaptive Optics – is required.

Shift and Add can sharpen images

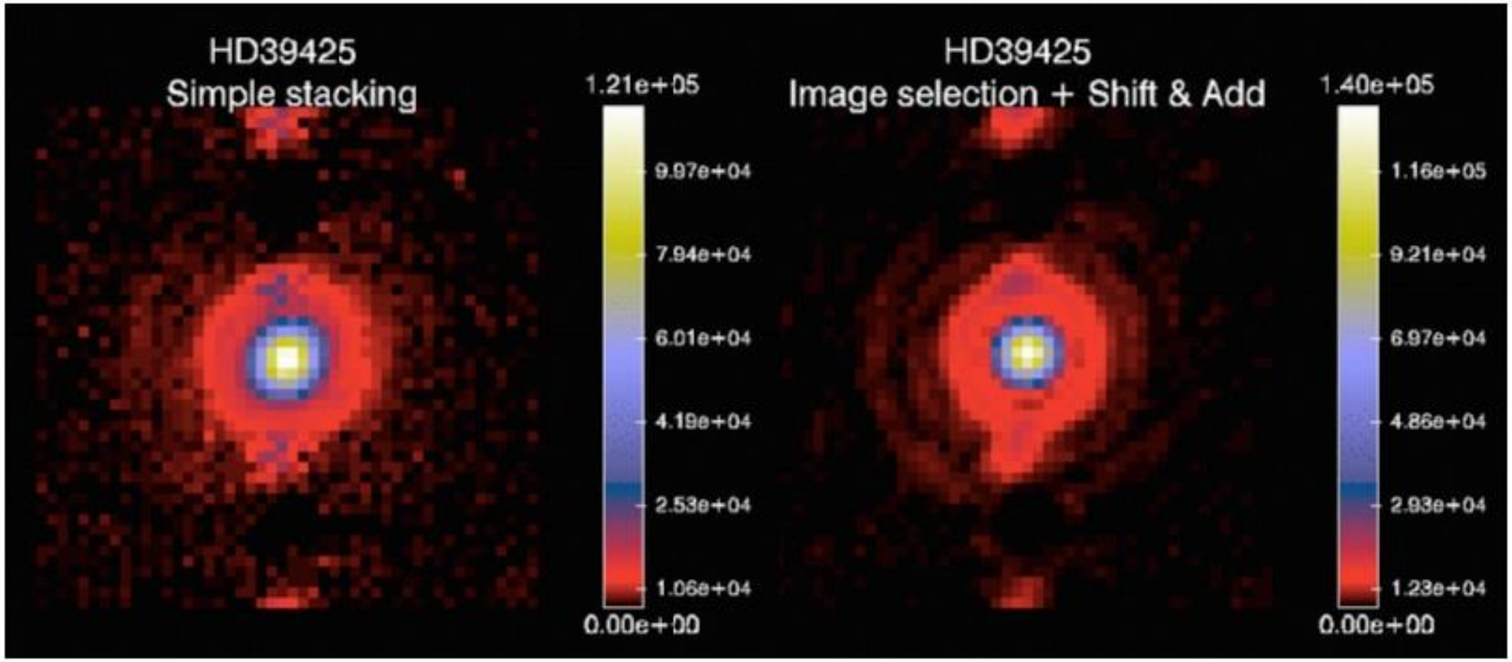


Figure 5. Left panel : simple stack of burst mode frames of the standard star HD39425, simulating a classical observation. Right panel, shift-and-add and image selection are applied to burst mode data. The average FWHM is decreased by 15% and the Strehl ratio is improved from 0.52 to 0.65. Note also the two unveiled diffraction rings (dark red) appearing in right panel.

Images with VISIR on the VLT demonstrate the improvements obtained with shift and add

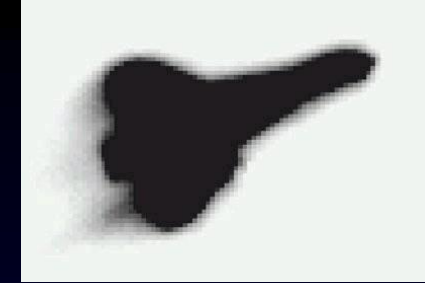
Achieving high resolution

- Diffraction-limited performance with single telescopes with Adaptive Optics
- Or sparse aperture masking
  - Use masks to sub-divide telescope primary into a number of subapertures which are combined interferometrically

(C32+((71484/75)*9.4))*1.05

  - http://www.eso.org/sci/publications/messenger/archive/no.146-dec11/messenger-no146-18-23.pdf
- Interferometry with 2 or more separated telescopes where the resolution depends on λ/b where b is the maximum baseline between apertures
- Plus: lunar occultations, speckle interferometry....

Adaptive Optics



The Space Shuttle imaged with AO from the Starfire Optical Range, Phillips AFB, NM

Proposed by Horace Babcock in 1953.
"The Possibility of Compensating Astronomical Seeing"

Developed by US military for satellite observations from the ground, and laser beam propagation.

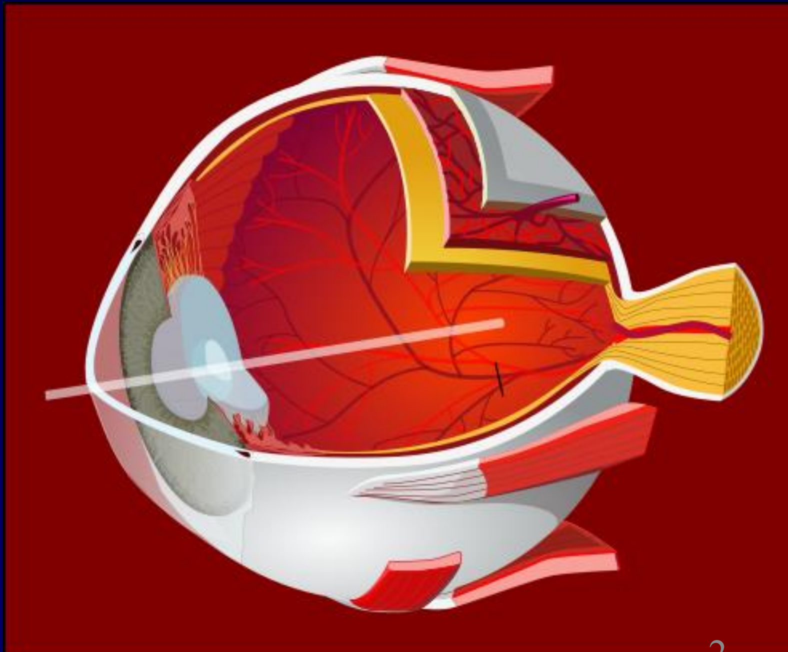
Astronomical developments in the 1990s as control systems evolved.

Now important in medical imaging and microscopy:

Imaging and spectroscopy of the retina, lens and cornea:

Diagnosis of diseases of the eye
- **Diabetic Retinopathy**
- **Macular degeneration**
- **………**

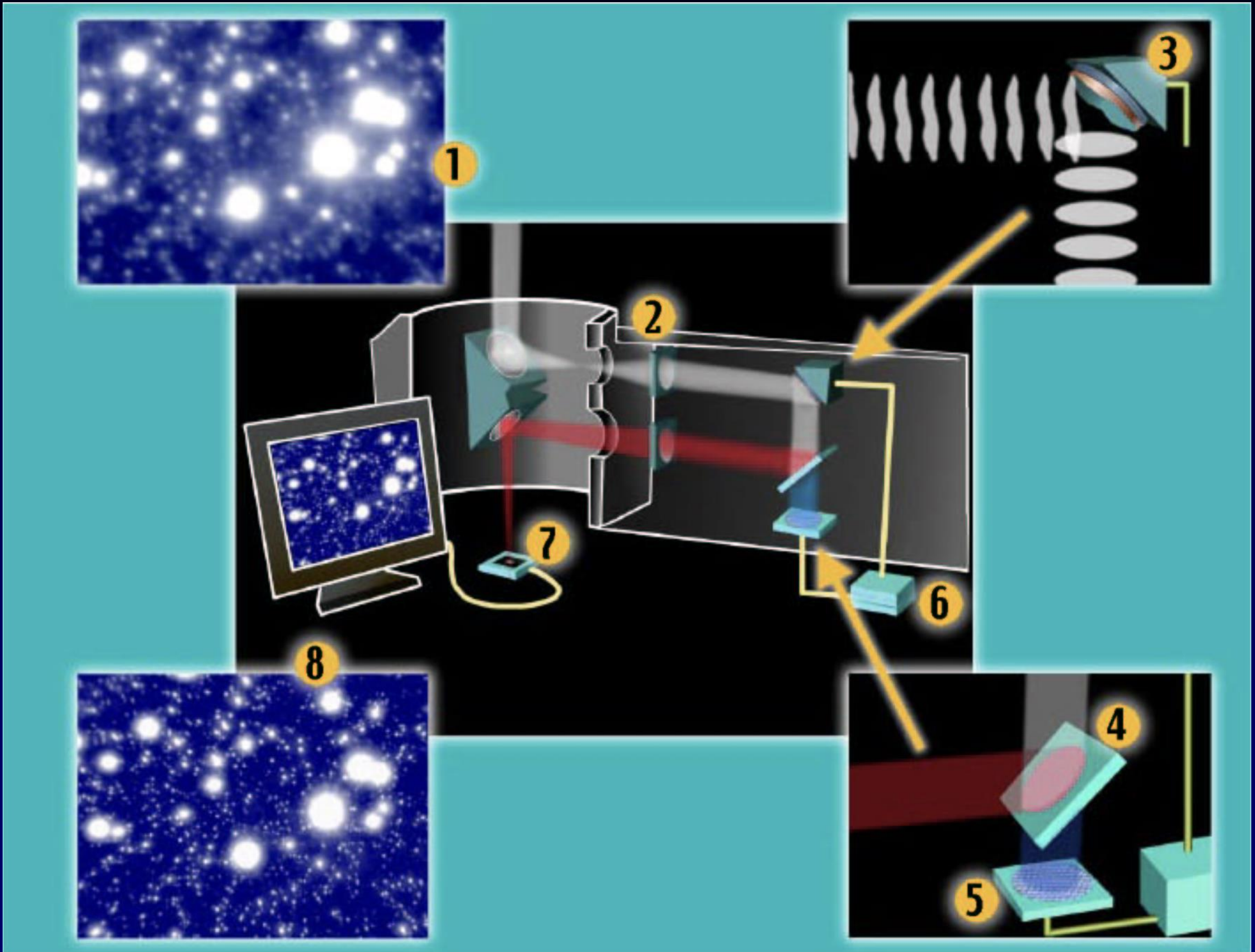
Window into the circulation and nervous system



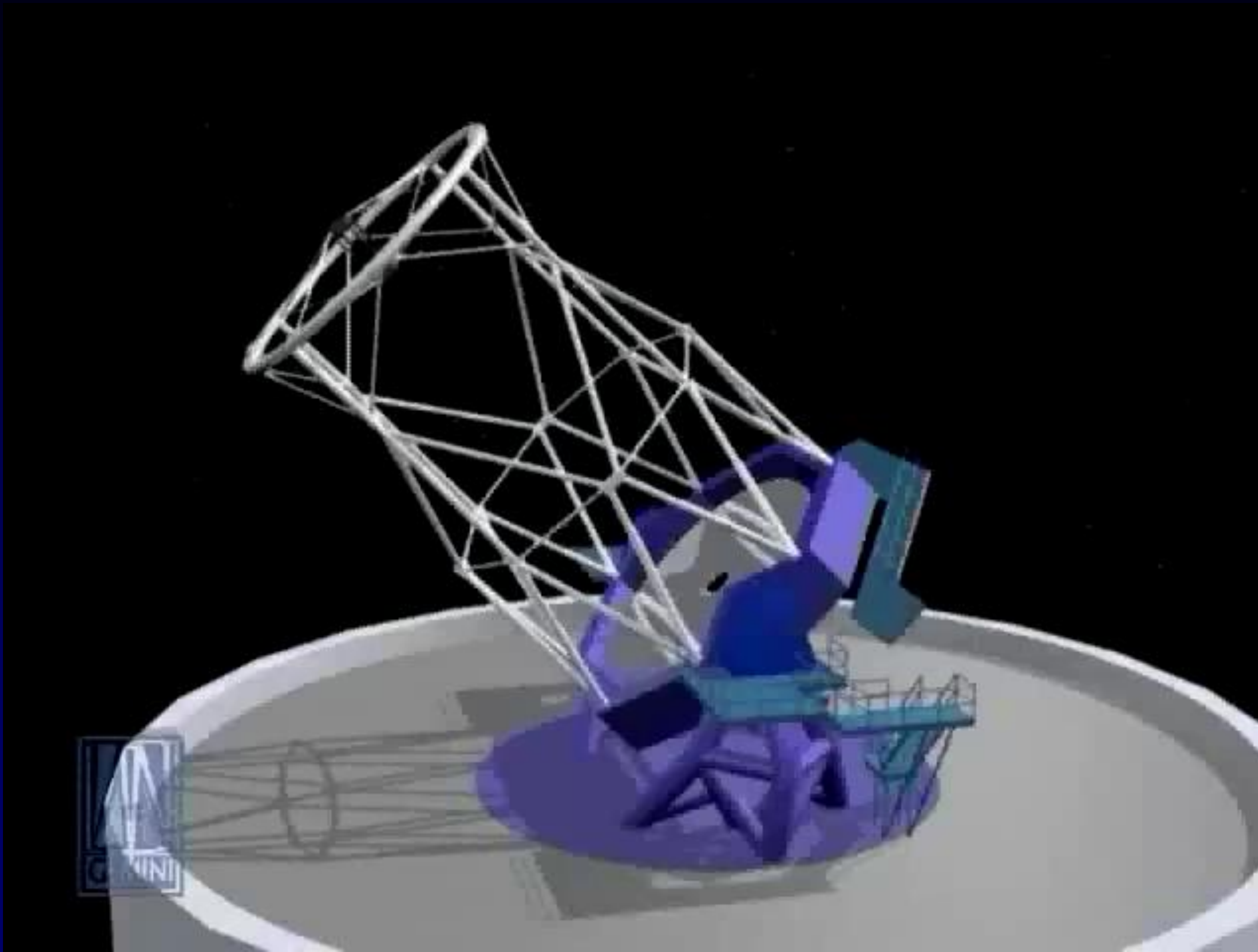
Adaptive Optics in Astronomy

- Real time compensation for atmospheric turbulence
- Restoring near-diffraction-limited performance at infrared wavelengths
- Now pushing image improvements to shorter wavelengths, larger fields, better and more stable image quality
- For detailed tutorials see.
  Claire Max: https://www.ucolick.org/~max/289/

Adaptive optics to the rescue



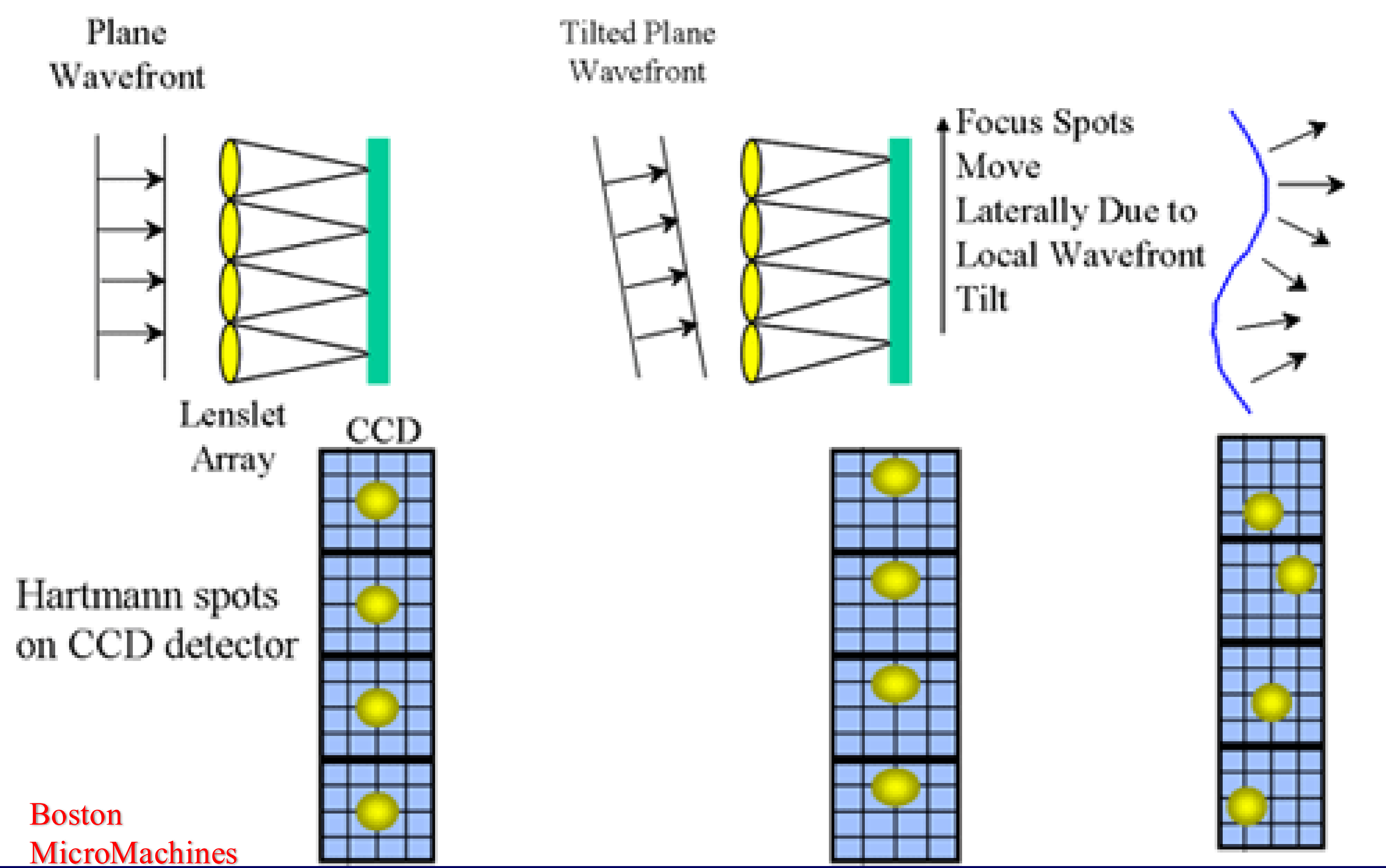
How does AO work?



A real demonstration

AO – real time computing and control challenges

- A number of different techniques are used for wavefront sensing, but the simplest conceptually is the Shack-Hartmann sensor
- The pupil is divided into a number of sub-apertures, typically each on the scale of r_0
- the tilt within each subaperture is determined by measuring the centroid of the sub-image – the displacement relative to the unaberrated pupil gives the tilt angle. A global reconstructor then estimates the overall shape
- A signal is applied to the matching actuators in the deformable mirror to counteract the tilt.
- This has to be done before the distortions change significantly



- Shack Hartmann WFS: For a large telescope, need 10s of subapertures across the pupil diameter and so the stellar flux from a guide star is divided into 100s or thousands of sub-apertures

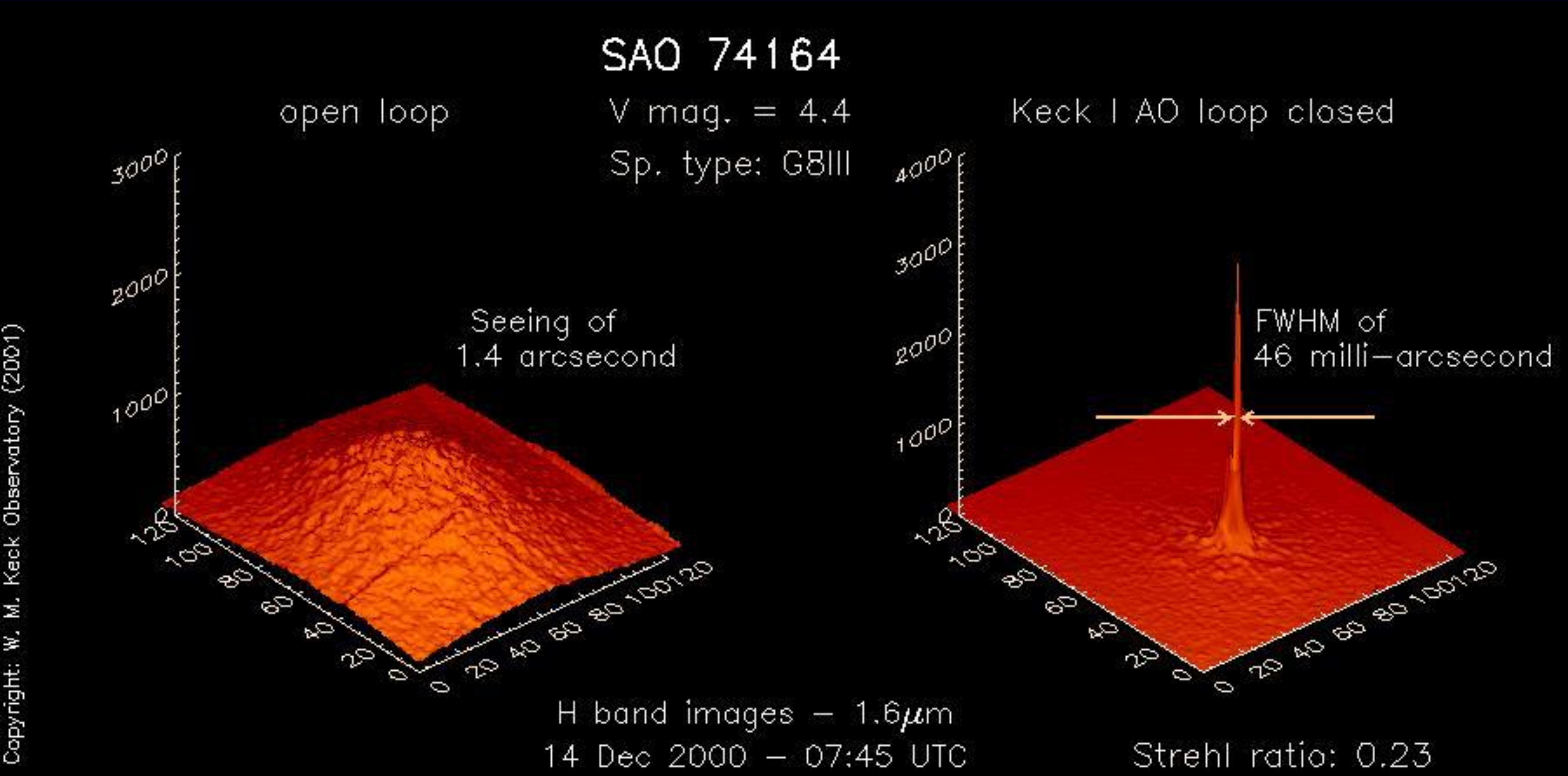
Practical Considerations

r_0 the turbulence coherence length, or Fried Parameter, is the typical size of turbulent cells in the atmosphere. Typically 5cm to 20cm in the visible at good sites

Angular isoplanatism – the angular measure over which a compensated wavefront can be considered planar ($<\pi$ radians). At visible wavelengths the isoplanatic angle is about 2 arc seconds increasing to 10 arc seconds in the near infrared.

- Compensation in visible wavelengths (0.5um) requires a guide star of magnitude 10 or brighter.
- Compensation in infrared wavelengths (2.2um) allows guide stars down to magnitude 14.
- Small isoplanatic region around the guide star limits targets
  - Visible – 1/100,000 of the sky
  - IR – 1/1000 of the sky

Strehl

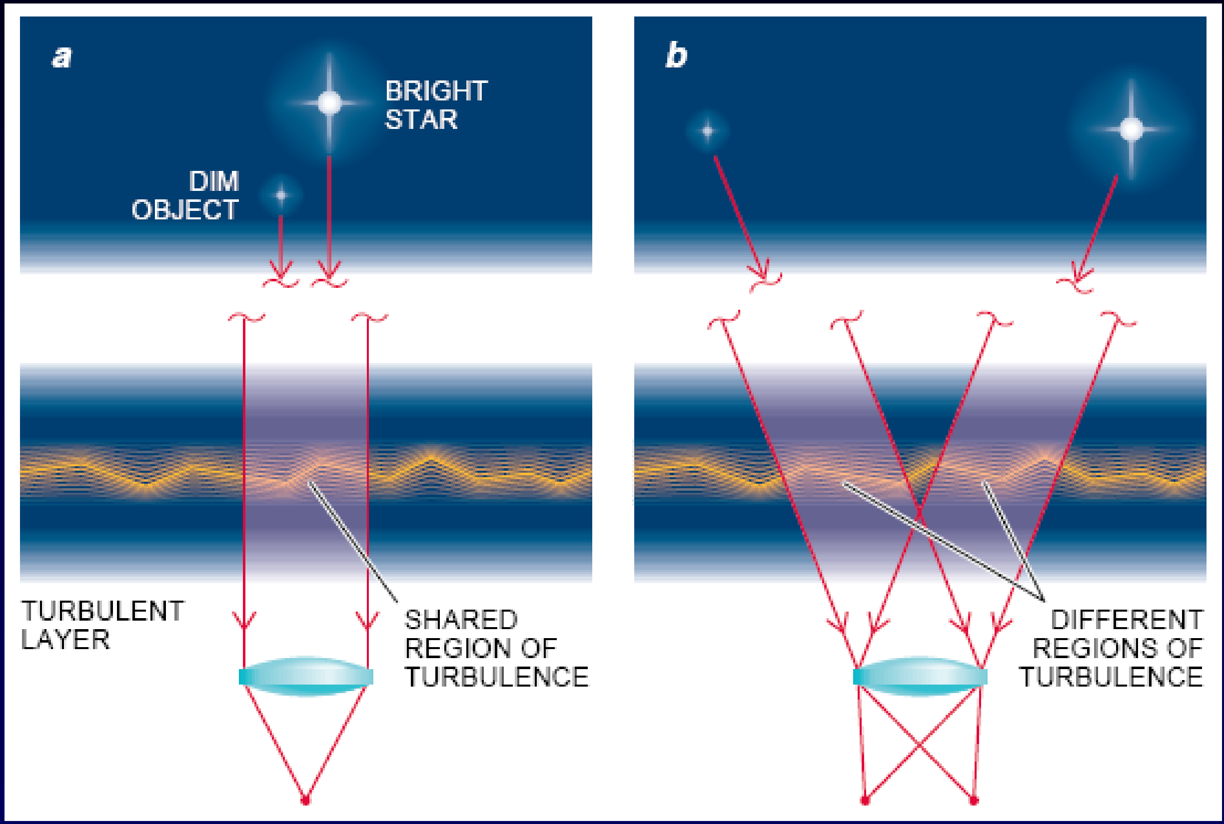


A measure of the quality of correction is the Strehl ratio – the fraction of intensity contained in the central maximum compared to the theoretical diffraction pattern

Isoplanatic Angle

Where a target is separated from a guide star by a significant angle, the column of turbulence along the path to the two objects diverges and leads to decorrelation.

AO correction falls off rapidly as the separation increases



The definition of the atmospheric isoplanatic angle θ_0 is

$$\theta_0 = 0.31 \; r_0 / \; h$$

where h is the characteristic altitude of turbulence

WFS Sensitivity Limits

With frame rates ~1kHz, and e.g. 20 x 20 subapertures, the photon flux/ sample/subaperture is $\sim 10^6$ times lower than the photon flux/sec gathered by the telescope.

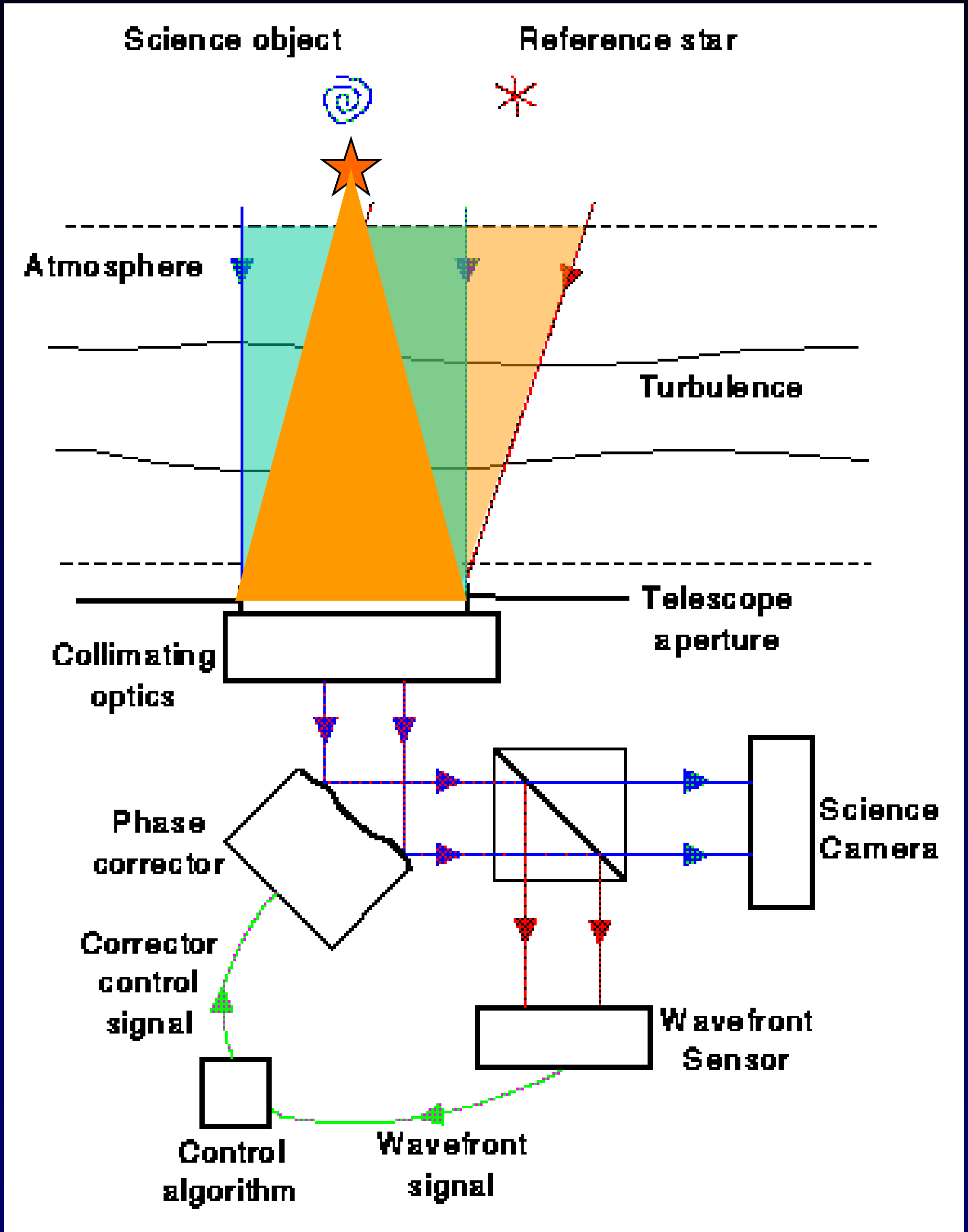
The light from each sub-aperture is imaged onto a small number of pixels and needs sufficient signal for the centroid to be measured.

The measurement error depends on the number of detected photons and α 1/SNR so there is a trade off between star brightness and quality of correction

With low-noise detectors, typically require stars of magnitude < 14 as AO guide stars for IR imaging

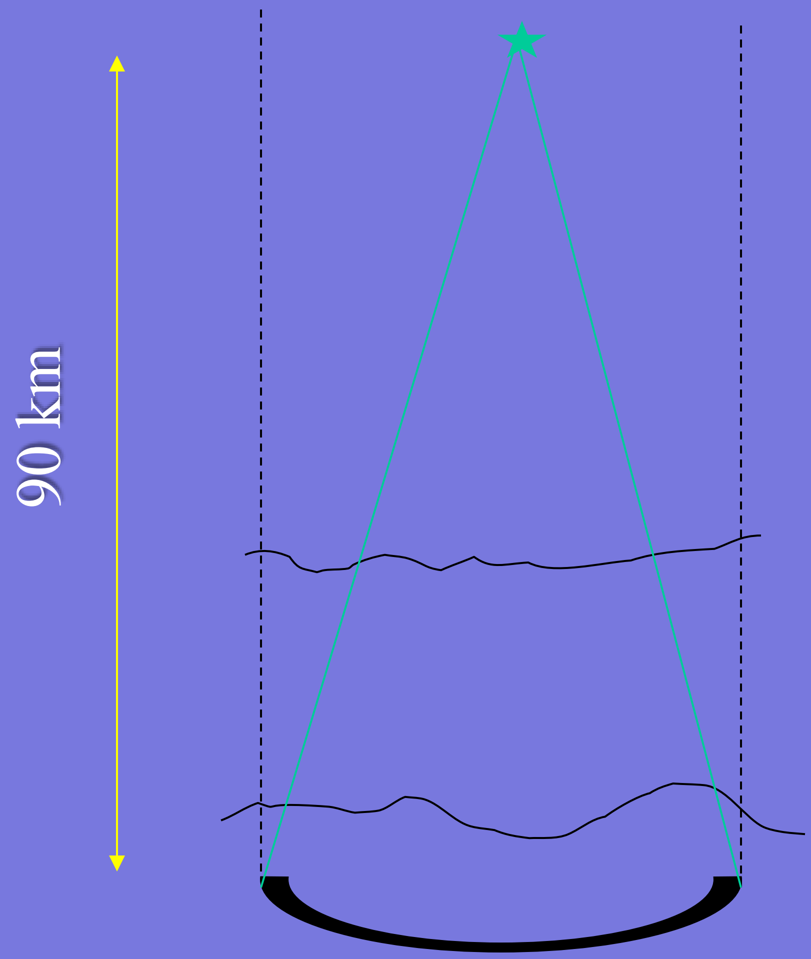
Twinkle, twinkle, laser star

Limitations of Laser Stars



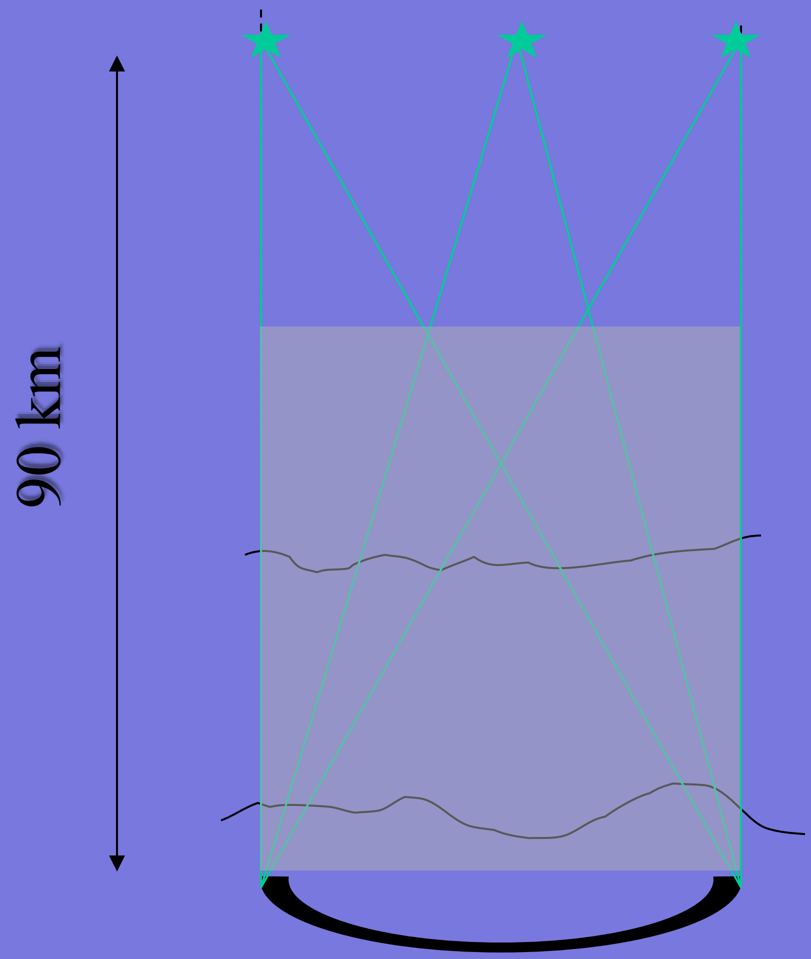
Tomography

1. Cone effect

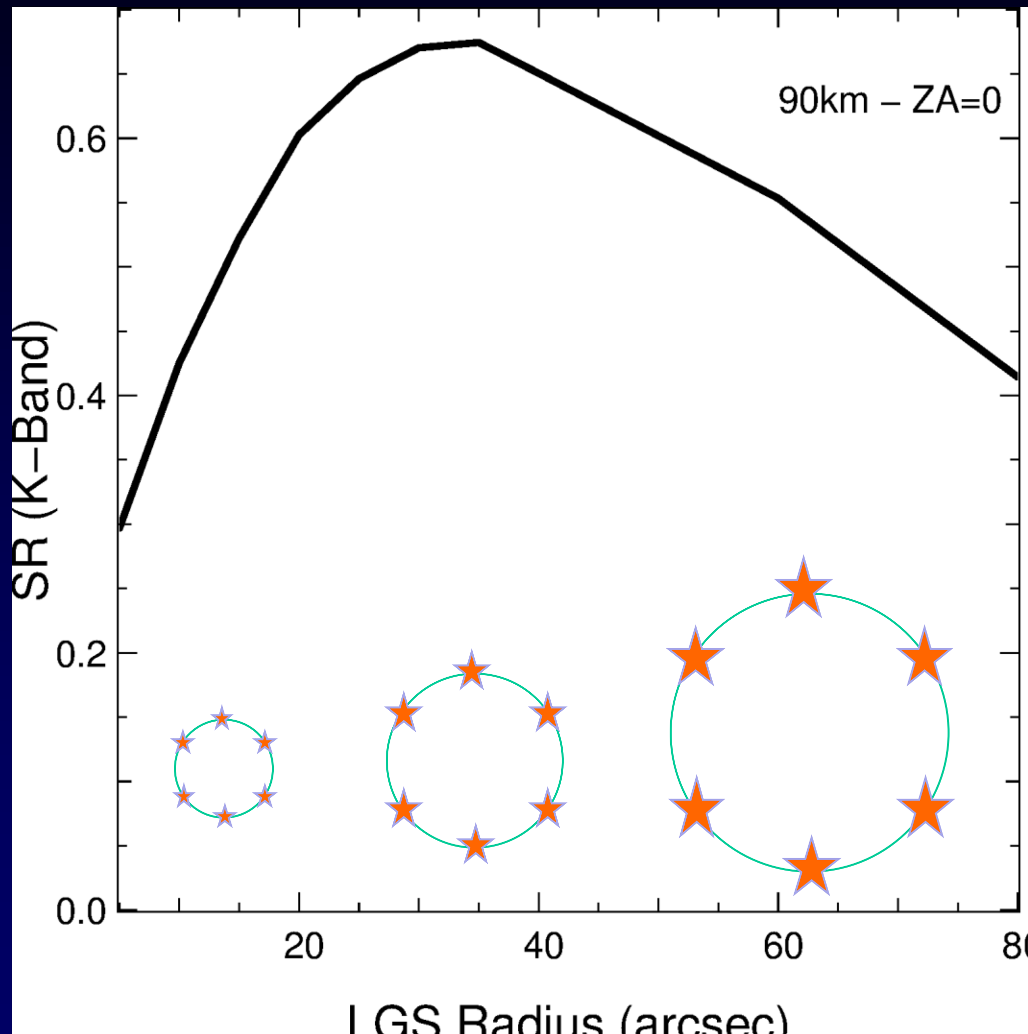


Tomography ?

2. Multiple guide star and tomography

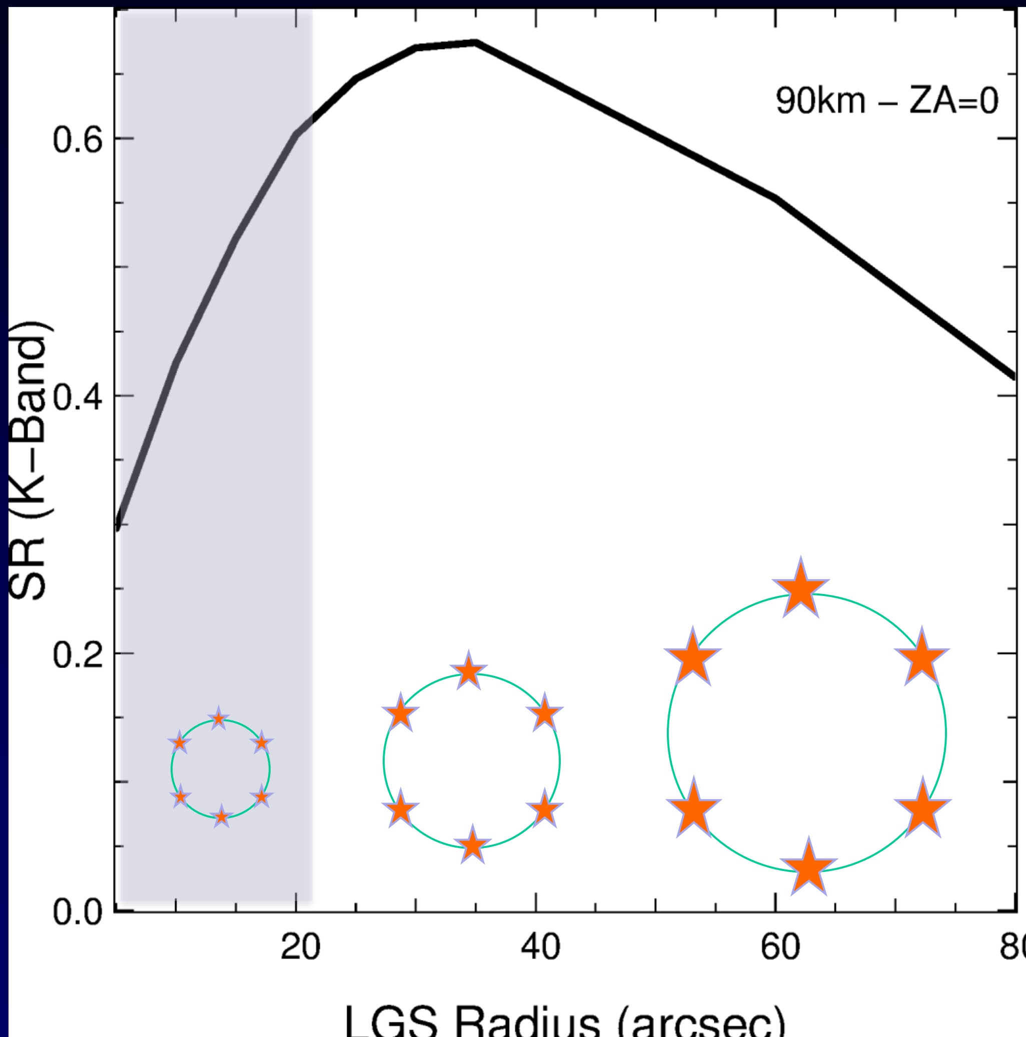


Impact of LGS constellation



Simulation from Miska Lelouarn (ESO – OCTOPUS) and Carlos Correia (OOMAO)

Impact of LGS constellation



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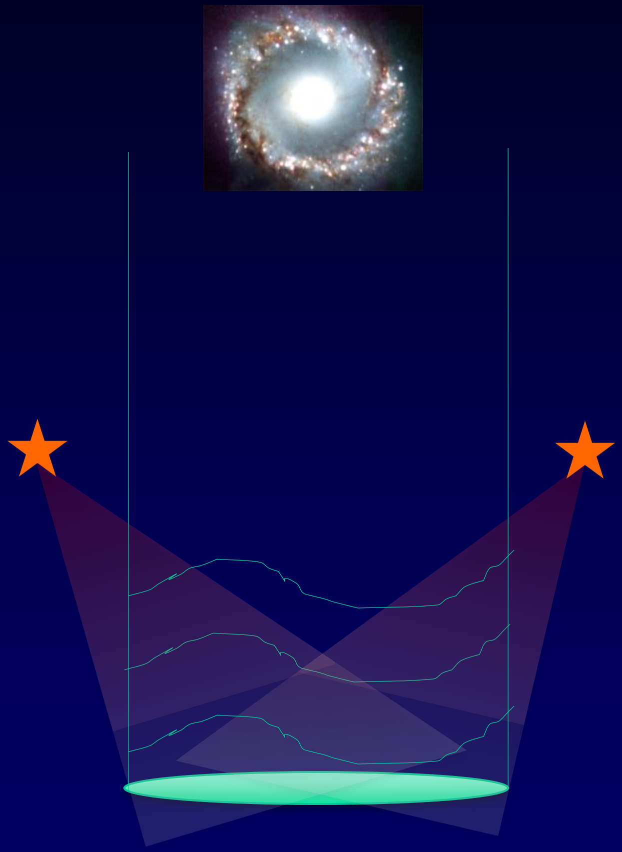
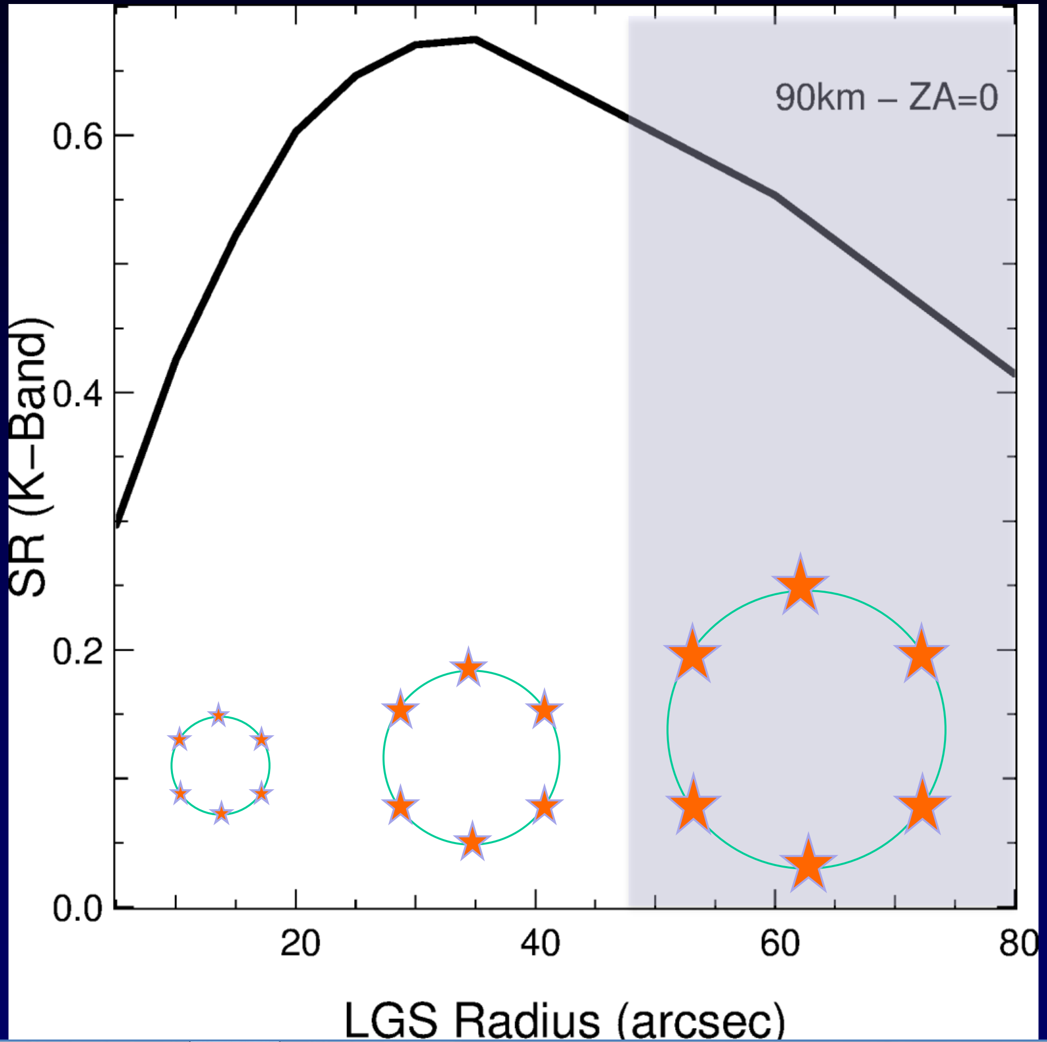
Impact of LGS constellation





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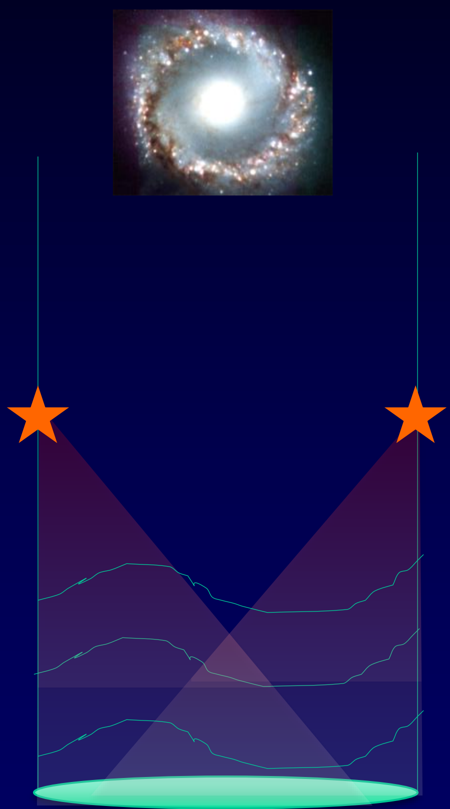

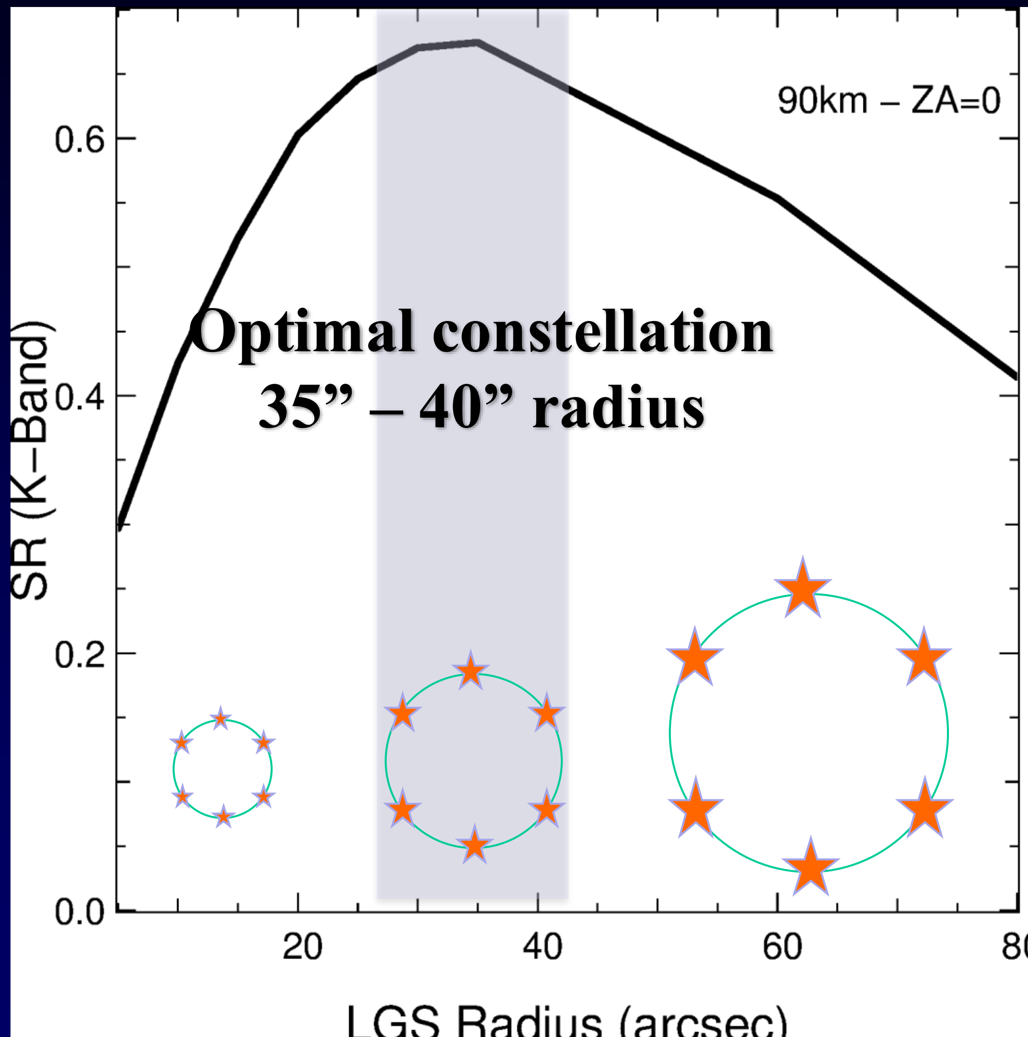

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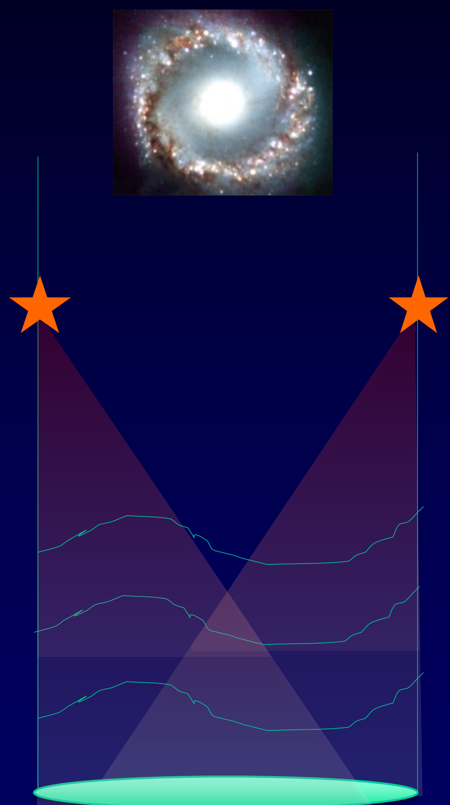
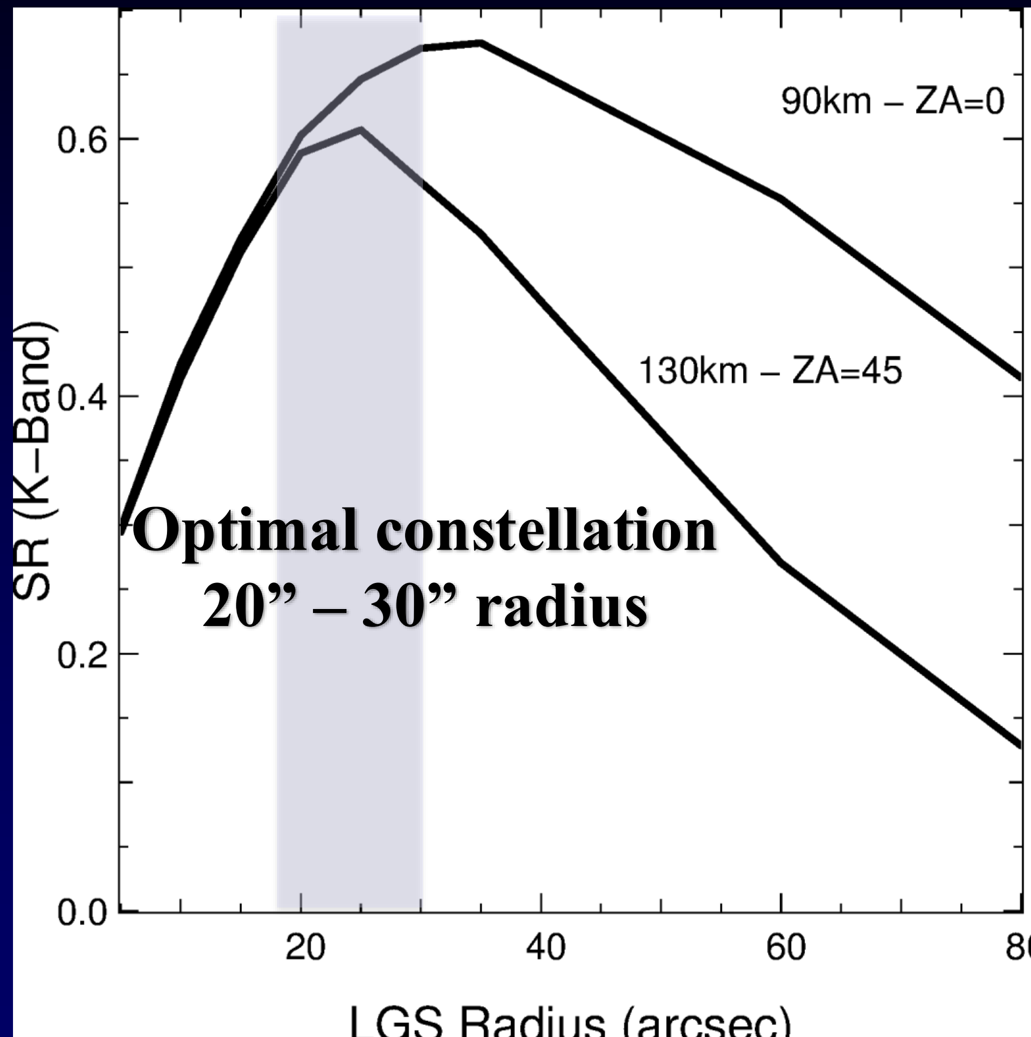
Impact of LGS constellation





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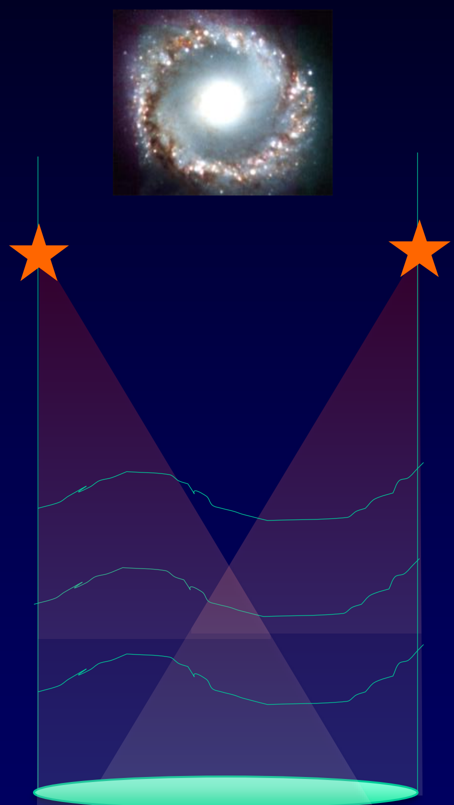
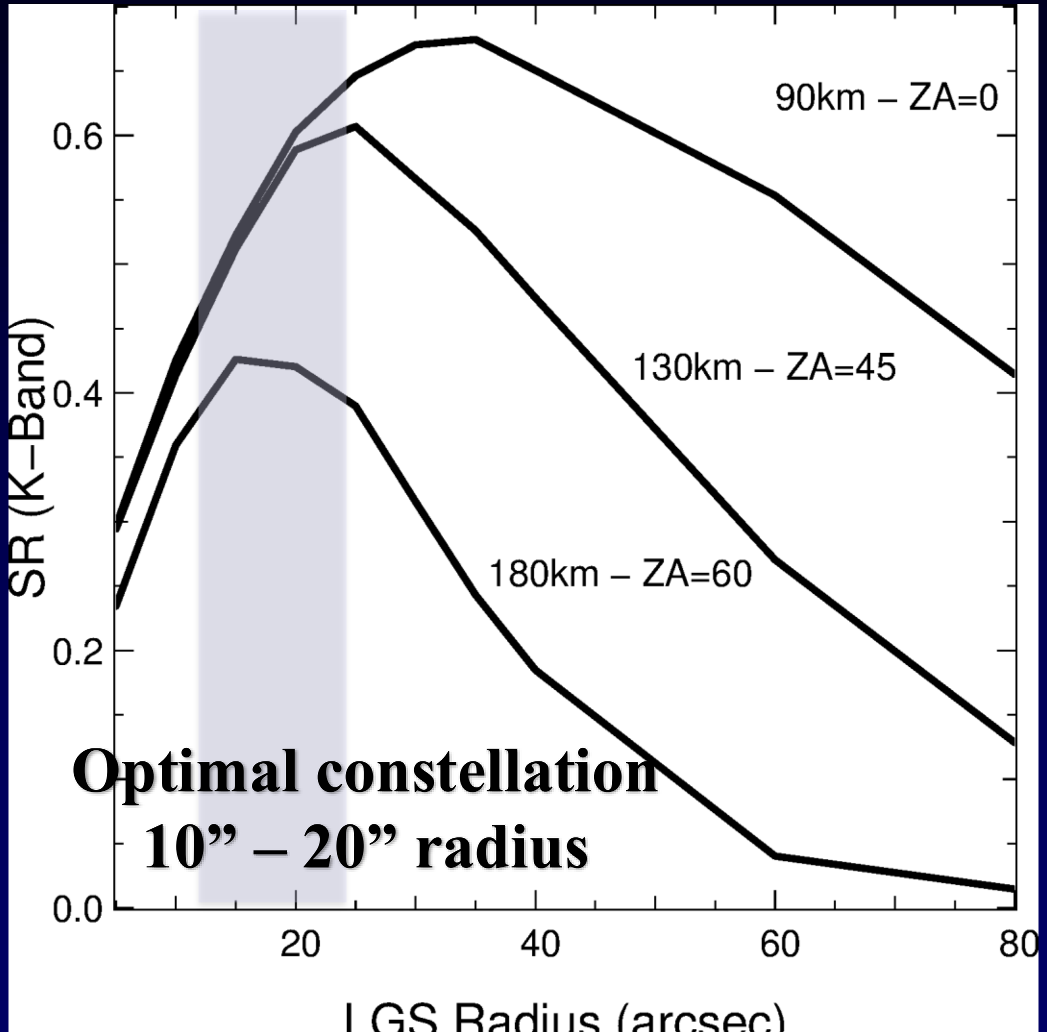
Impact of LGS constellation

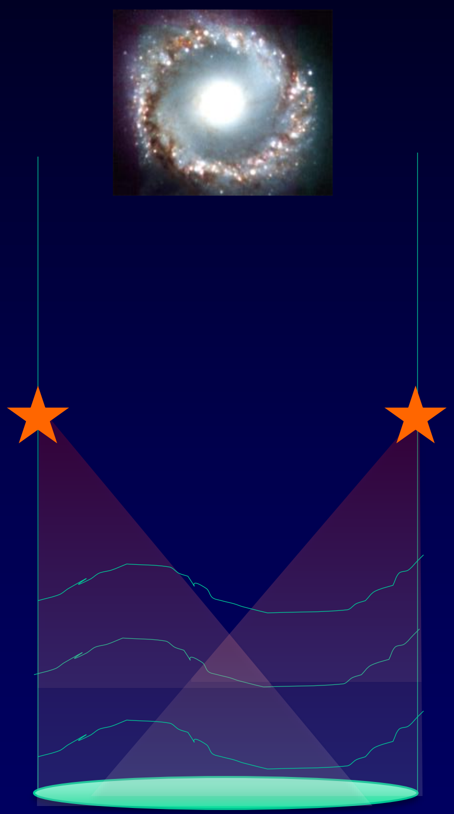


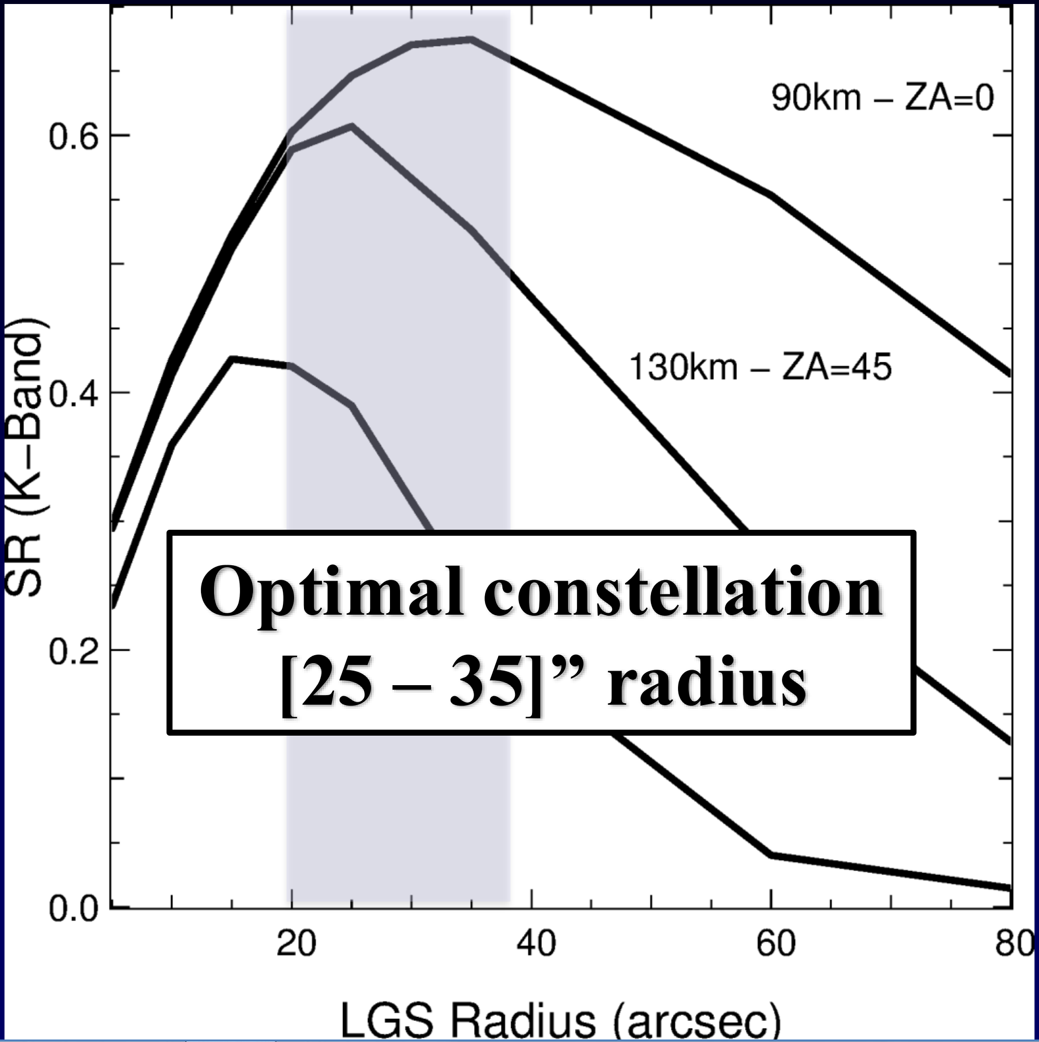


Optimal constellation
10” – 20” radius

Simulation from Miska Lelouarn (ESO – OCTOPUS) and Carlos Correia (OOMAO)

Impact of LGS constellation





Simulation from Miska Lelouarn (ESO – OCTOPUS) and Carlos Correia (OOMAO)

Limitations of Laser Stars

The laser beam passes through the atmosphere up to the sodium layer and the tilt component causes the position of the star to wander.

A natural guide star is used as the tilt component reference.

The cone of light from the LGS samples a subset of the cylinder that the telescope beam encompasses so it does not cover some turbulence : focal anisoplatism or the Cone effect

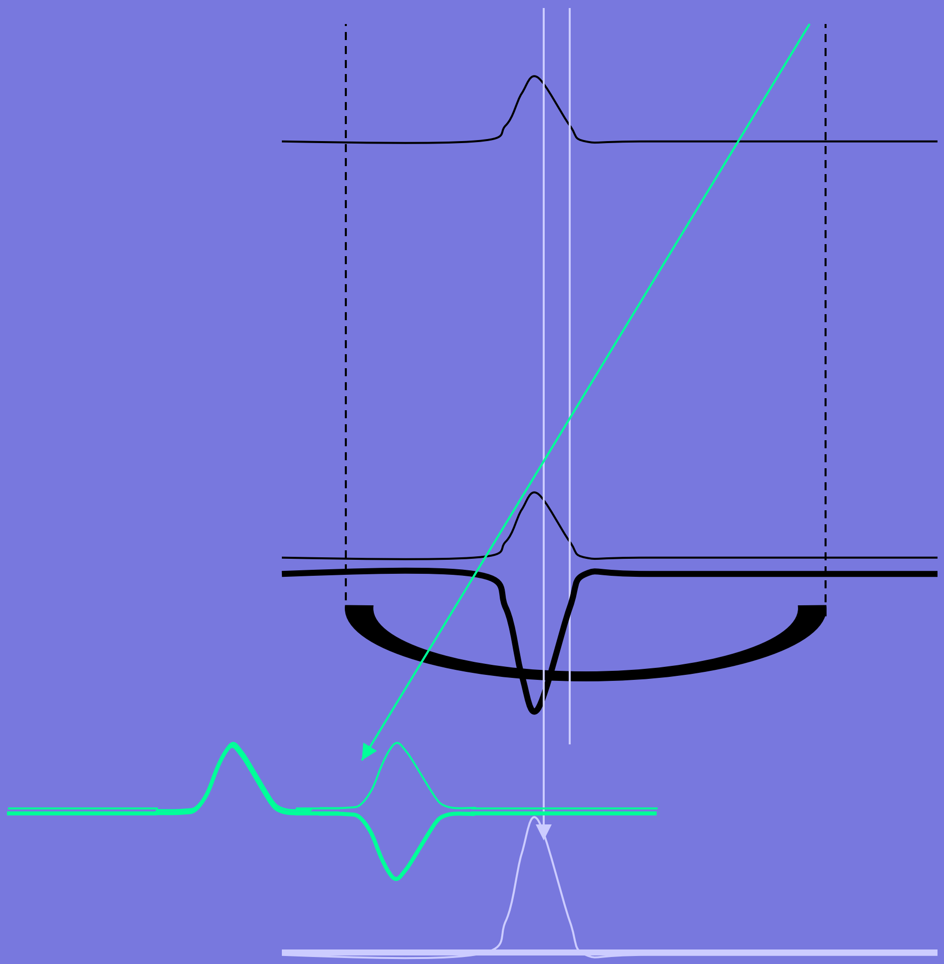
Produces ~2arcsec ‘star’ at zenith, which is elongated at higher airmass due to Na layer thickness.

The distance to the sodium layer increases with zenith distance, so continuous refocussing or path length compensation is required.

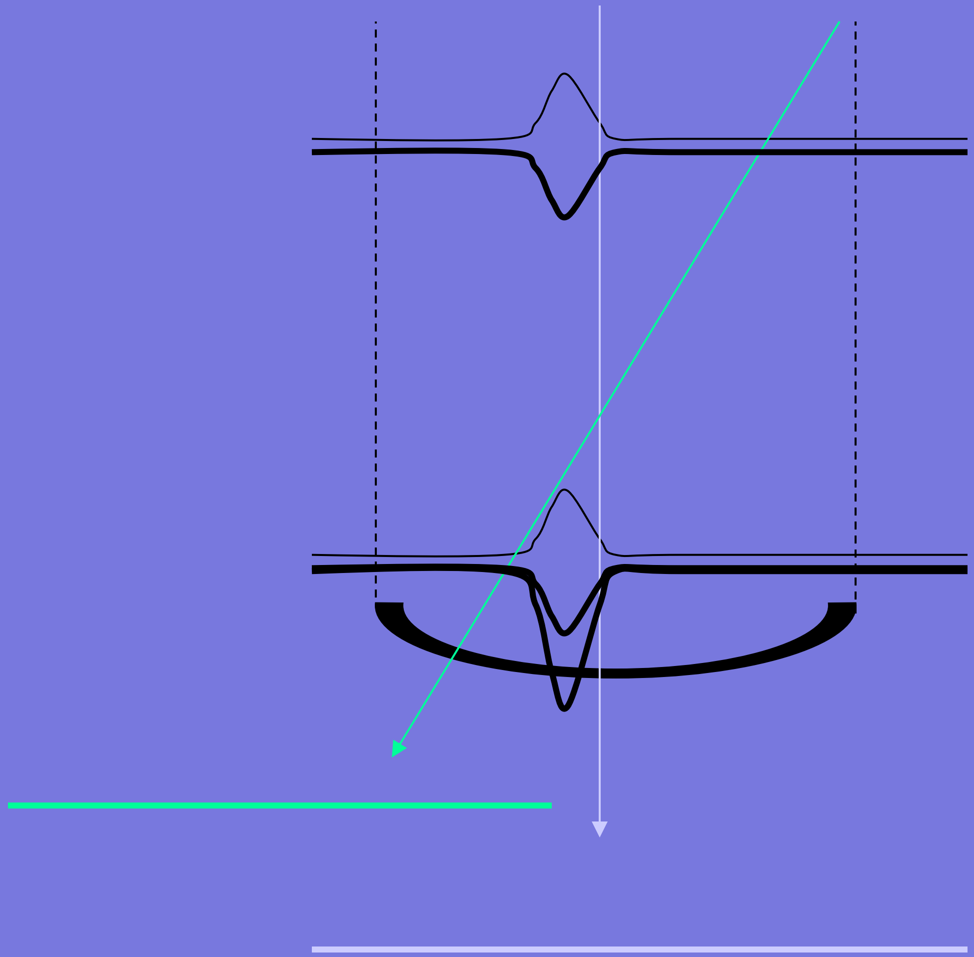
Advanced AO

- 4 (or more) LGS in a constellation can cover the full cylinder and give improved correction
- Combined with multiple deformable mirrors (DMs), conjugated to different altitudes, this gives complete sampling and improved correction for the atmosphere.
- Multi-conjugate AO - e.g GEMS at Gemini-S
- Xtreme AO with high density actuators to give very high strehl images – e.g for exoplanet searches

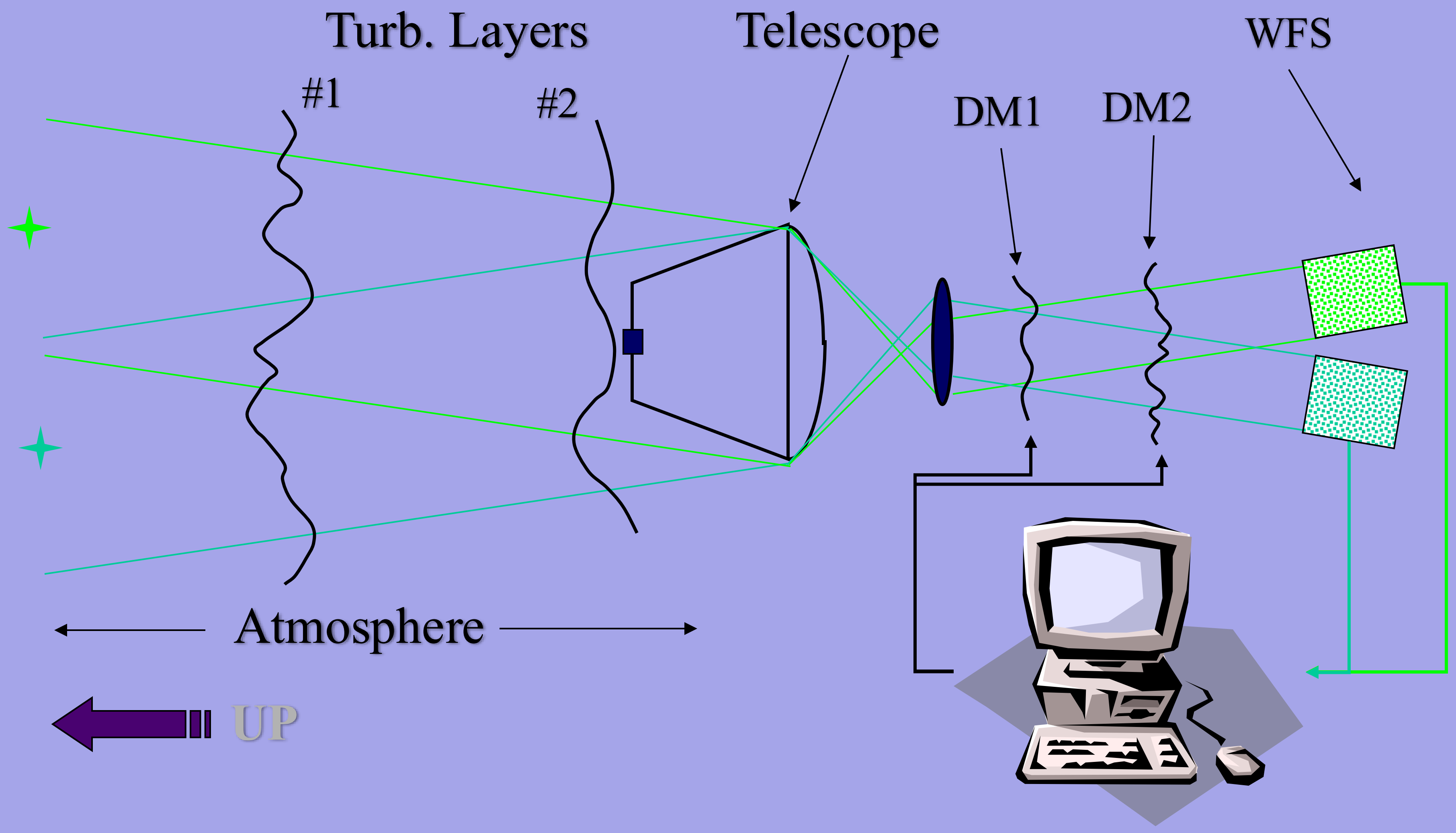
Multiconjugate



What is multiconjugate?

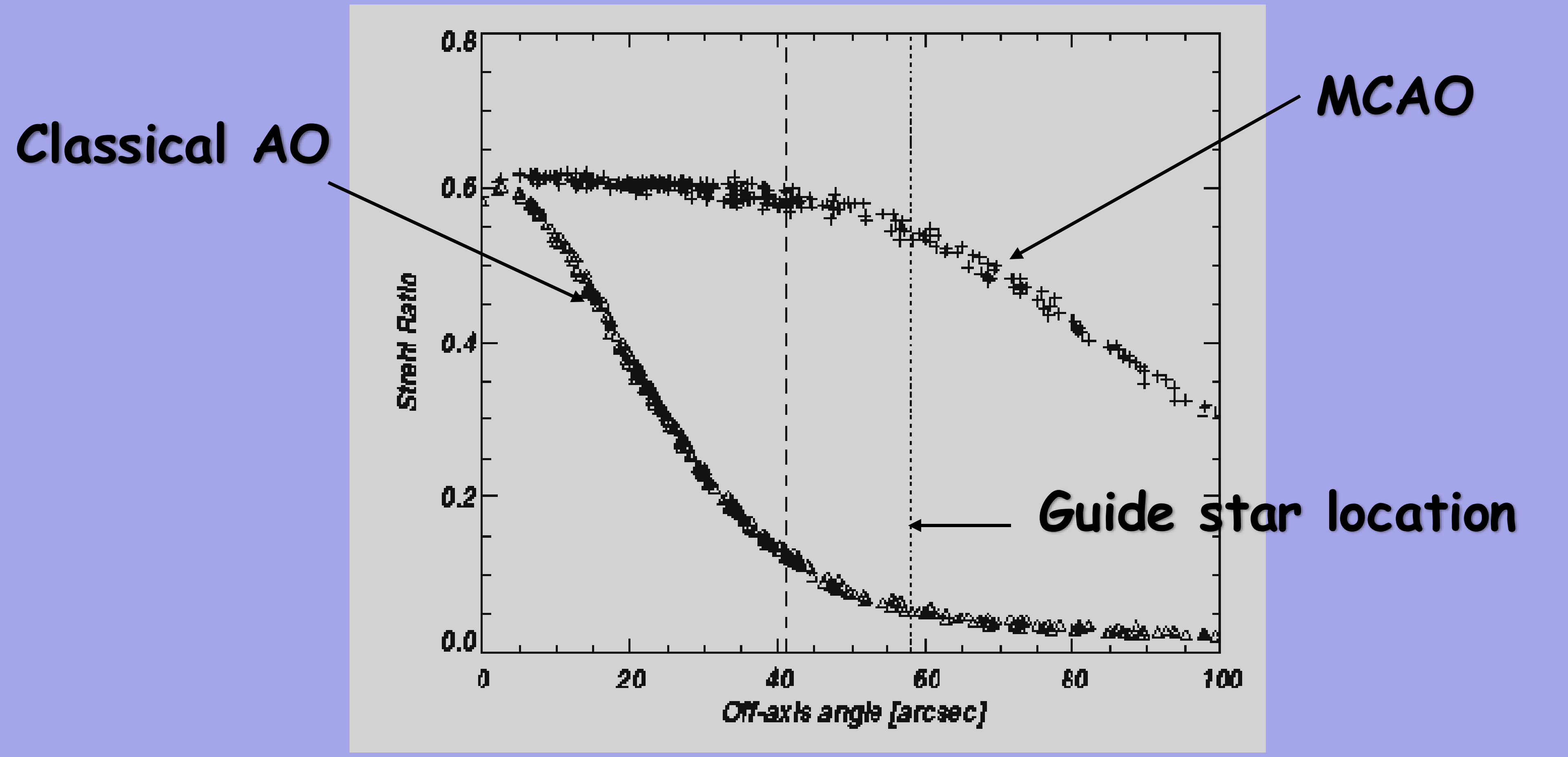


Multiconjugate AO



MCAO Performance Summary

Early NGS results, MK Profile



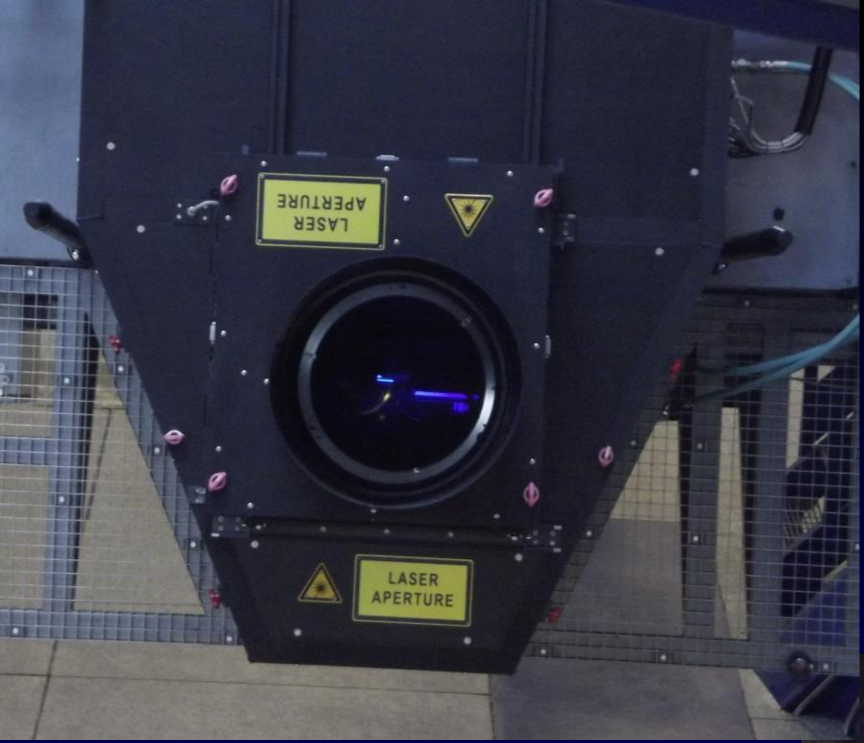
Laser Guide Stars

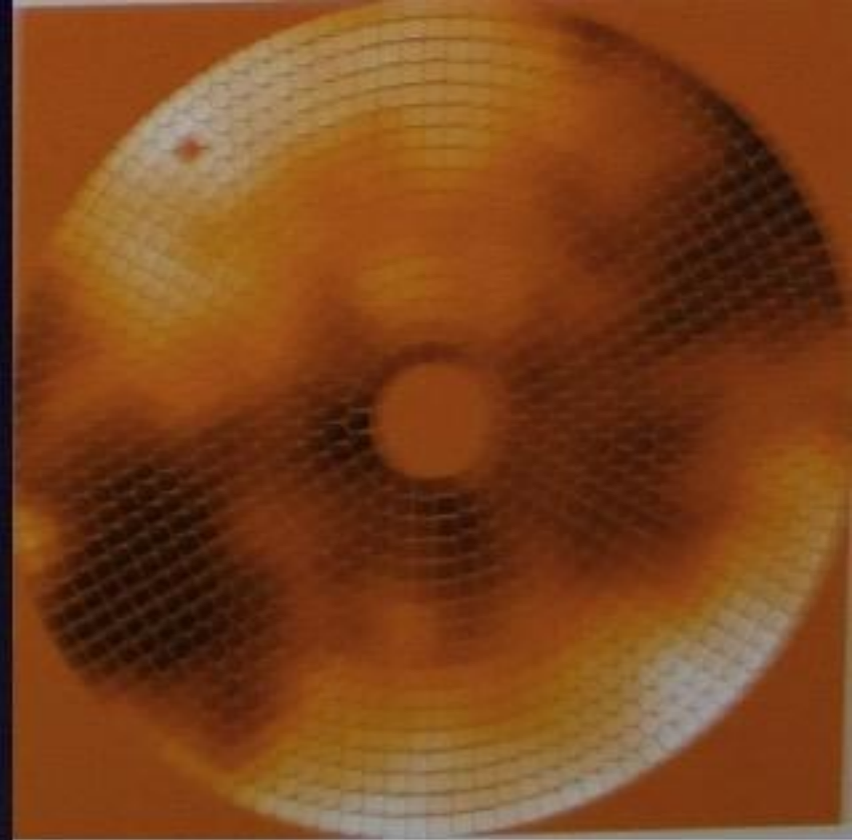
Substantial development programmes in sodium lasers, wavefront sensors, deformable mirrors, reconstructors and control systems

GEMS : LGS MCAO system on Gemini-S feeding GSAOI (Infrared AO Imager) or FLAMINGOS (IR Multi-object Spectrometer)

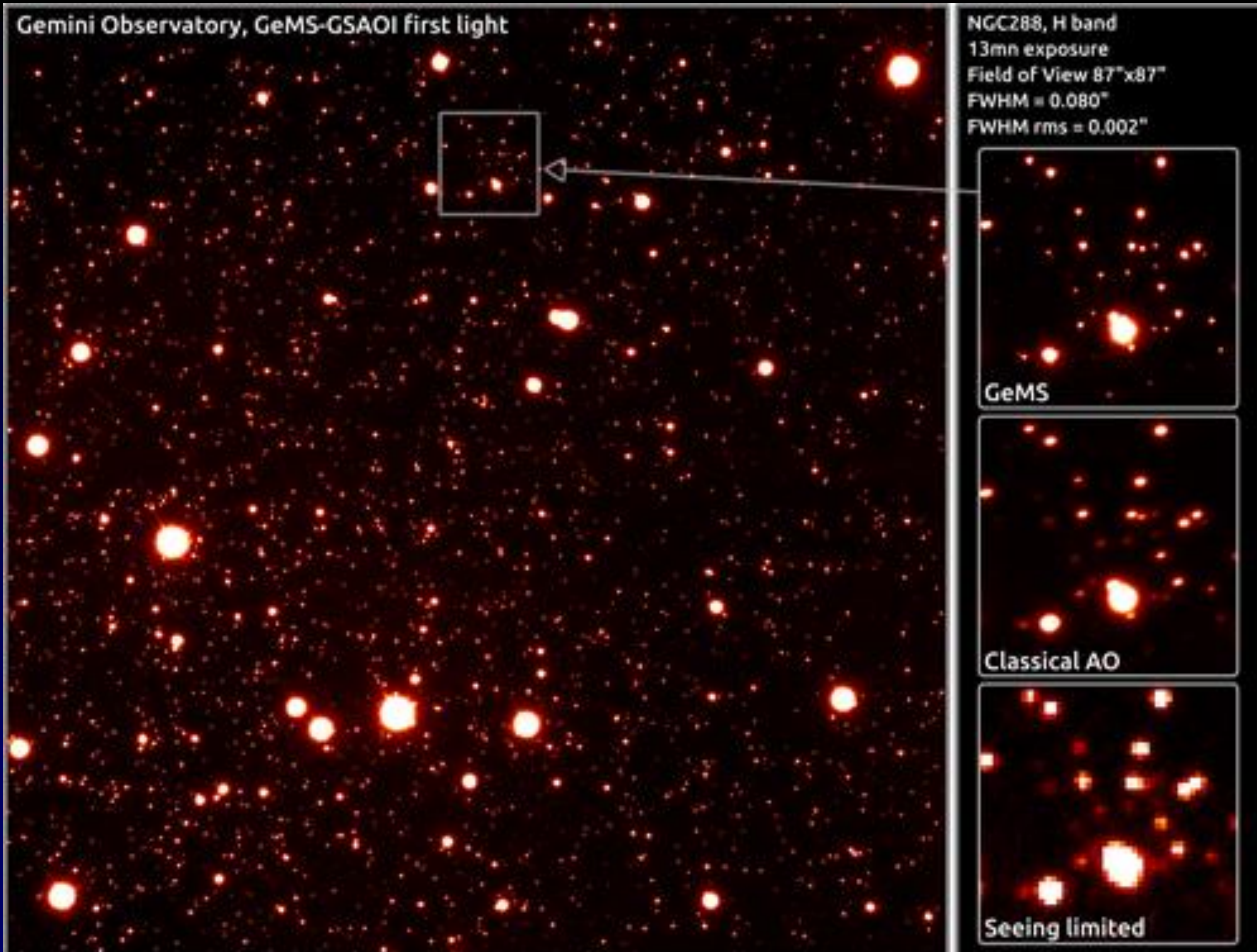
VLT AOF on UT4 is operating at Paranal feeding Hawk-I or MUSE

VLT UT4 Laser launch telescopes





The LGS constellation produced by the adaptive Optics Facility at the UT4 telescope of the ESO VLT. Light from the LGS is used to estimate the wavefront distortions and corrections are applied to the deformable secondary mirror. The image above shows a snapshot of the phase corrections applied to the secondary.


Gemini Observatory, GeMS-GSAOI first light
NGC288, H band
13mn exposure
Field of View 87"x87"
FWHM = 0.080"
FWHM rms = 0.002"
GeMS
Classical AO
Seeing limited

Different AO Flavours

Method		Corrected field of view
Laser Tomography AO	LTAO	10's of arc sec
Multi-Object AO	MOAO	N x 10's of arc sec
Multi-Conjugate AO	MCAO	≤ about 2 arc min
Ground Layer AO	GLAO	A few to 10 arc min

+ Extreme AO - aimed at very high Strehl on bright Natural Guide Stars – exoplanet searches